**Question 1 (20 points)**

Determine whether the following statements are "True" or "False". No motivation/explanation has to be given. Each wrong answer deducts 4 points from the total (down to 0 points).

(a) Skipping flight only applies to ballistic vehicles

(b) Increasing the nose radius of a vehicle will decrease the lift-to-drag ratio

(c) A gliding entry is characterized by a large angle of attack at the beginning of entry

(d) For a transformation between two reference frames you always need three unit-axis rotations

(e) Euler angles give the preferred attitude representation because they are singularity free

(f) In an exponential atmosphere model, the speed of sound is independent from the altitude

(g) To determine the 3D position from GPS signals more than three GPS satellites are required

(h) The eigenvalues of a non-linear system describe the characteristic motion of this system

(i) Parachute reefing is used to lower the mechanical loads on the system

(j) In skipping flight the maximum mechanical load occurs after the maximum heat flux, contrary to ballistic entries

**Question 2 (30 points)**

Consider the motion of an arbitrary re-entry vehicle in the atmosphere of the Earth

(a) **6 points.** Draw a clear sketch of the 2D (in-plane) motion of this vehicle with respect to a spherical, non-rotating Earth with a fixed inertial reference frame. Indicate the state variables velocity, altitude and flight-path angle, as well as the external forces of aerodynamic and gravitational origin. Note to pay attention to the correct orientation of forces and state variables.

(b) **6 points.** Starting with the sketch obtained under a), set up the general equations of motion for a re-entry flight in the directions parallel with and perpendicular to the velocity vector. Also provide the equation for the time rate of change of the altitude.

(c) **6 points.** Assume that the vehicle is flying a ballistic trajectory. Show that the trajectory of the vehicle is a straight line. Clearly state the assumption(s) that you make to simplify the equations of motion.

(d) **10 points.** The typical flight duration of a ballistic vehicle is in the order of a few minutes. That means that in a very short time all kinetic energy is transformed into heat. To avoid excessive thermo-mechanical loads, for manned vehicles a so-called gliding entry is executed. One of the characteristics is a much longer flight time. Show that the flight time for gliding entry is given by $t_{flight} = \frac{V_c}{2g}\frac{L}{D}\ln\left(\frac{1+V_E/V_c}{1-V_E/V_c}\right)$.

(e) **2 points.** Calculate the actual flight time for this gliding vehicle.

Additional data for this question: the vehicle with lift-to-drag ratio $L/D = 2$ enters the atmosphere with an entry velocity of 80% of the circular velocity ($V_c = 7.92$ km/s). The gravitational acceleration can be assumed to be constant and is $g = 9.81$ m/s$^2$.

**Question 3 (20 points)**

The Mars Science Laboratory uses a combination of parachutes and landing engines to decrease its velocity. Close to the surface, it operates as a sky crane to lower a rover while it hovers above the surface. In this question we consider a similar vehicle and mission configuration.

(a) **4 points.** After hypersonic descent and sequential parachute phase the velocity of the vehicle has decreased to 100 m/s at 1.8 km altitude. At that moment the parachute is released. For a vertical flight, set up the equations of motion for the successive powered flight.

(b) **4 points.** In case the landing engines fail to ignite for 5 seconds, what will be the velocity at the beginning of the powered phase? One may assume an average (= constant) vehicle drag of 2500 N.

(c) **3 points.** What is the corresponding altitude?

(d) **4 points.** To lower the rover to the surface of Mars, the descent vehicle is hovering for 13 seconds. What would be the throttle setting if all 8 engines are used simultaneously? How much fuel is used during that timespan? Assume a (constant) vehicle mass at the beginning of the hovering phase of $m = 1200$ kg.

(e) **3 points.** What can you say about the maximum acceleration error that you make by having assumed a constant mass? Quantify the error (note: assume a fuel-mass consumption of $m_{fuel} = 32$ kg if you could not answer question (d)).

(f) **2 points.** What happens with the vehicle if the engines are not throttled to compensate for this error?

Additional data for this question: the gravitational acceleration can be assumed to be constant and is $g_{Mars} = 3.69$ m/s$^2$ and $g_{Earth} = 9.81$ m/s$^2$. The initial vehicle mass is 2196 kg, whereas the 8 engines provide a thrust of 3000 N each and have a specific impulse of 200 s (Earth referenced).

**Question 4 (30 points)**

To minimize the mass of the thermal protection system the trajectory should be flown such that the integrated heat load is minimized. To achieve that one should fly along the maximum heat-flux constraint as long as possible. This question deals with the design of such a tracking guidance.

(a) **6 points.** Given the definition of the heat-flux error, $q_{\mathrm{c,err}} = q_c - q_{\mathrm{c,setpoint}}$, define the three components of a PID controller

(b) **10 points.** For heat-flux tracking the heat flux should remain constant during a major portion of the flight, *i.e.*, $\dot{q}_c = 0$. Starting with Chapman's equation for the heat flux ($q_c = \frac{c_1}{\sqrt{R_N}}\sqrt{\rho}V^3$), derive an expression for the nominal drag force, $D_{cmd,0}$ that fulfills this requirement. An exponential atmosphere can be assumed.

(c) **4 points.** As $D_{cmd,0}$ is only the nominal drag, define a PI-controller to compensate for perturbations in the heat flux. Also, give the complete expression for the commanded drag, $D_{cmd}$.

(d) **5 points.** Given that the drag coefficient is a function of angle of attack and Mach number, how does one obtain the commanded angle of attack, $\alpha_{cmd}$ from $D_{cmd}$?

(e) **5 points.** Identify the parameters that should be obtained by the navigation system. How do you propose to get these parameters? Hint: think about the type of (non-ideal) sensors and use global terms only (no equations required).